# Coherent diffraction imaging with partially coherent discharge plasma based EUV sources

**Larissa Juschkin, Jan Bußmann, Raoul Bresenitz, Mikheil Mebonia**
RWTH Aachen University and PGI-9, Forschungszentrum Jülich

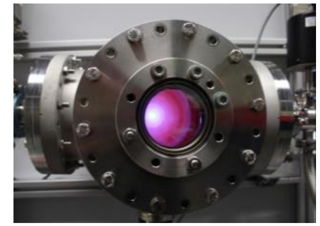
**Michal Odstrcil, William S. Brocklesby**
University of Southampton

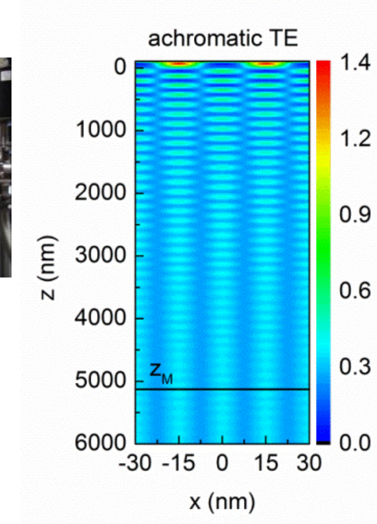
**Yusuke Teramoto,** BLV Licht- und Vakuumtechnik GmbH, Aachen

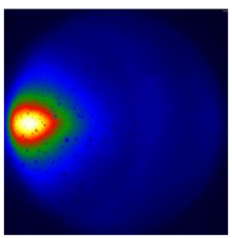
**Marco Perske, Torsten Feigl,** Optixfab GmbH, Jena

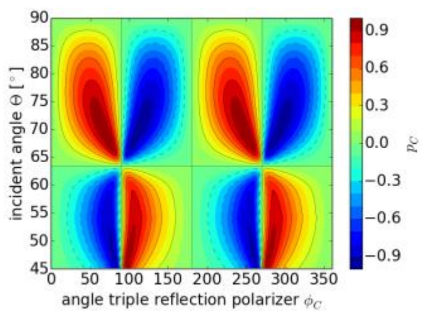
# EUV group fields of research at RWTH/FZJ

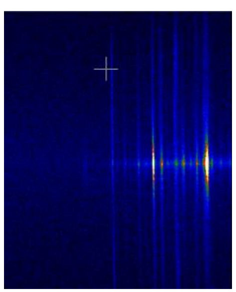
- Applications of extreme ultraviolet radiation in nanostructuring and metrology including
  - ✓ EUV microscopy and imaging
  - ✓ EUV lithography and nanostructuring
  - ✓ Scatterometry and coherent diffractive imaging
  - ✓ Soft X-ray and EUV spectroscopy and reflectometry
  - ✓ Photo-electron emission spectroscopy and microscopy
- Soft X-ray and EUV compact radiation sources

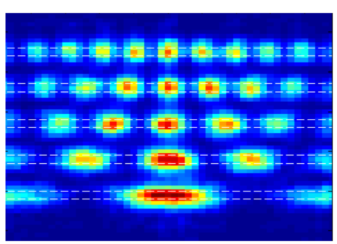


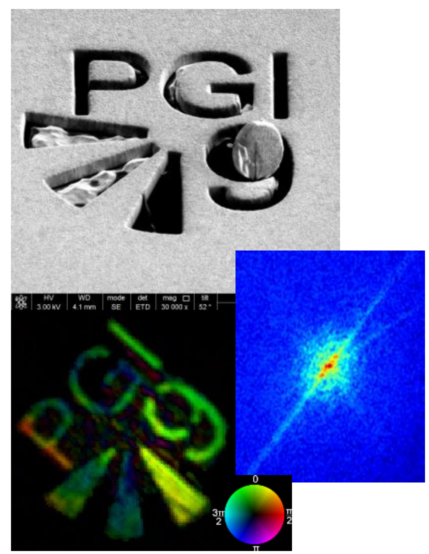


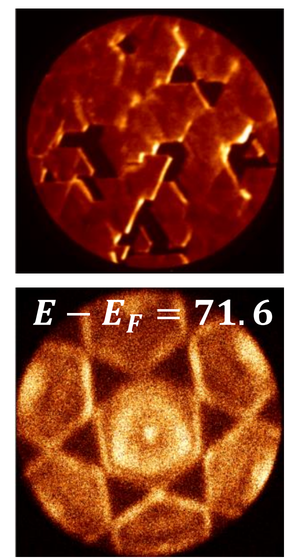



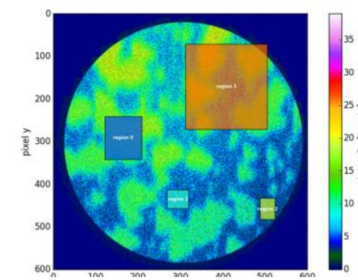


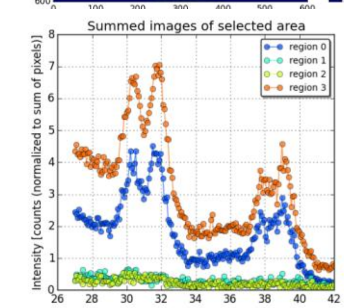








L. Juschkin, 2016 Workshop on EUV and Soft X-ray Sources, Nov. 7-9, Amsterdam

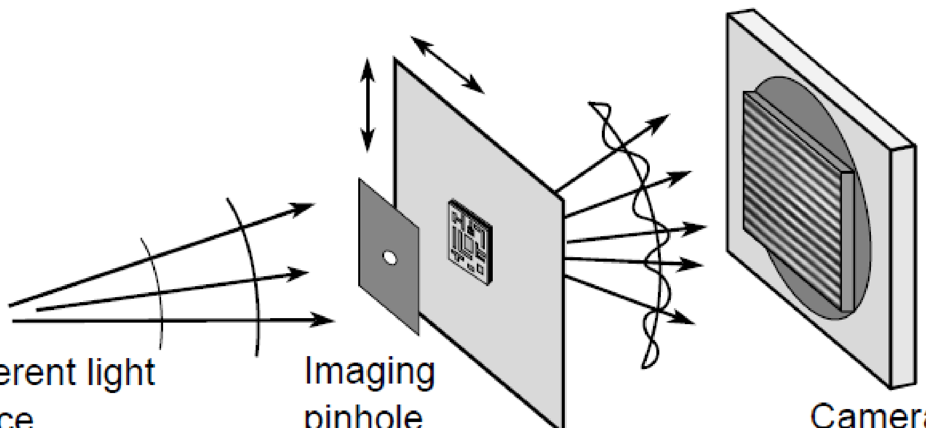
Experimental Physics of Extreme Ultraviolet

# Motivation –
# Why CDI is interesting for us?

CDI advantages comparing to standard optical microscopy:

- Not limited by quality of optics
- Large depth of focus
- More compact setup, easier alignment
- Better use of incidence light => lower dose
- Reconstruction of phase shift and attenuation

**particularly suited for imaging with short wavelength radiation**

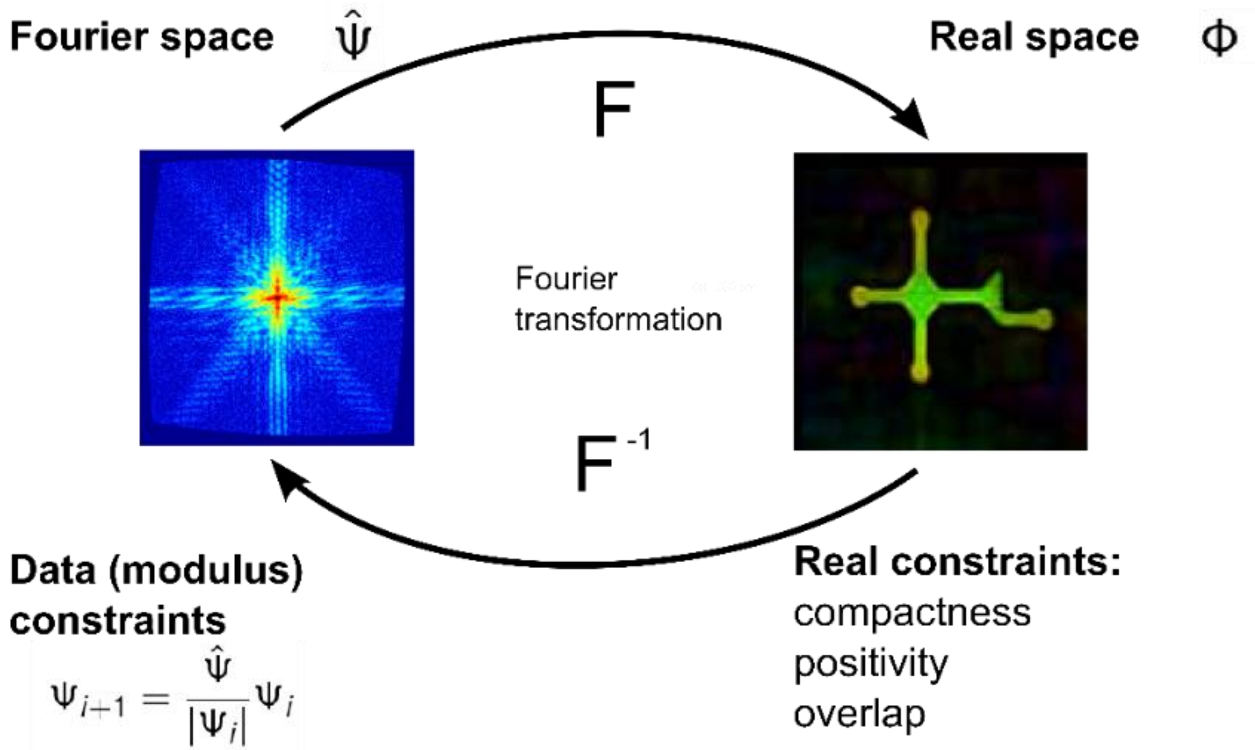



**XUV: short wavelength and strong light matter interaction**

**lateral & in-depth (3d) nm resolutions with element sensitivity and high throughput**

# Reconstruction

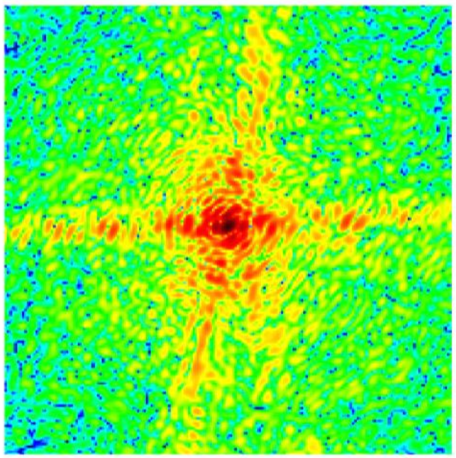
- Knowledge of measured intensity and a compact object with known support allows iterative reconstruction
- Different algorithms can be used (ER, HIO, GHIO, ...) only changing the way data outside of the support is handled



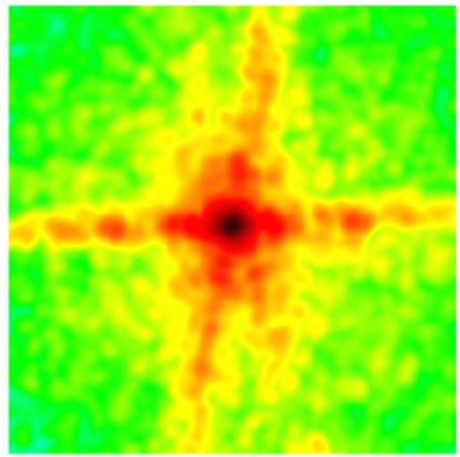

- In each iteration step corrections for blurring, noise, etc. can be performed
- Error metric allows to see convergence of the reconstruction to a solution / minimum

# Effect of limited coherence on diffraction pattern

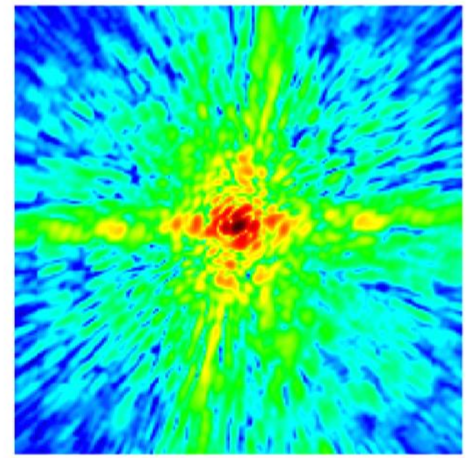
- Diffraction patterns are only sharp if incident light is coherent



**perfect coherence**



**spatial incoherence**



**temporal incoherence**

- **Object has to be compact and smaller than (half) the coherence width**
- $$N_{pixel} = \frac{\lambda}{\Delta\lambda} \cdot \frac{1}{O}$$

**O: oversampling**

➢ homogeneous blurring

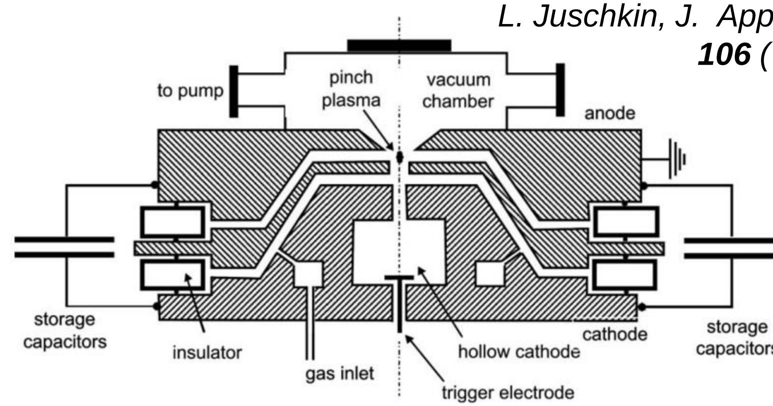
➢ scaling from center

$\Rightarrow$ Use of apertures for spatial and multilayer mirrors for temporal filtering and accounting for blurring and bandwidth in reconstruction algorithm

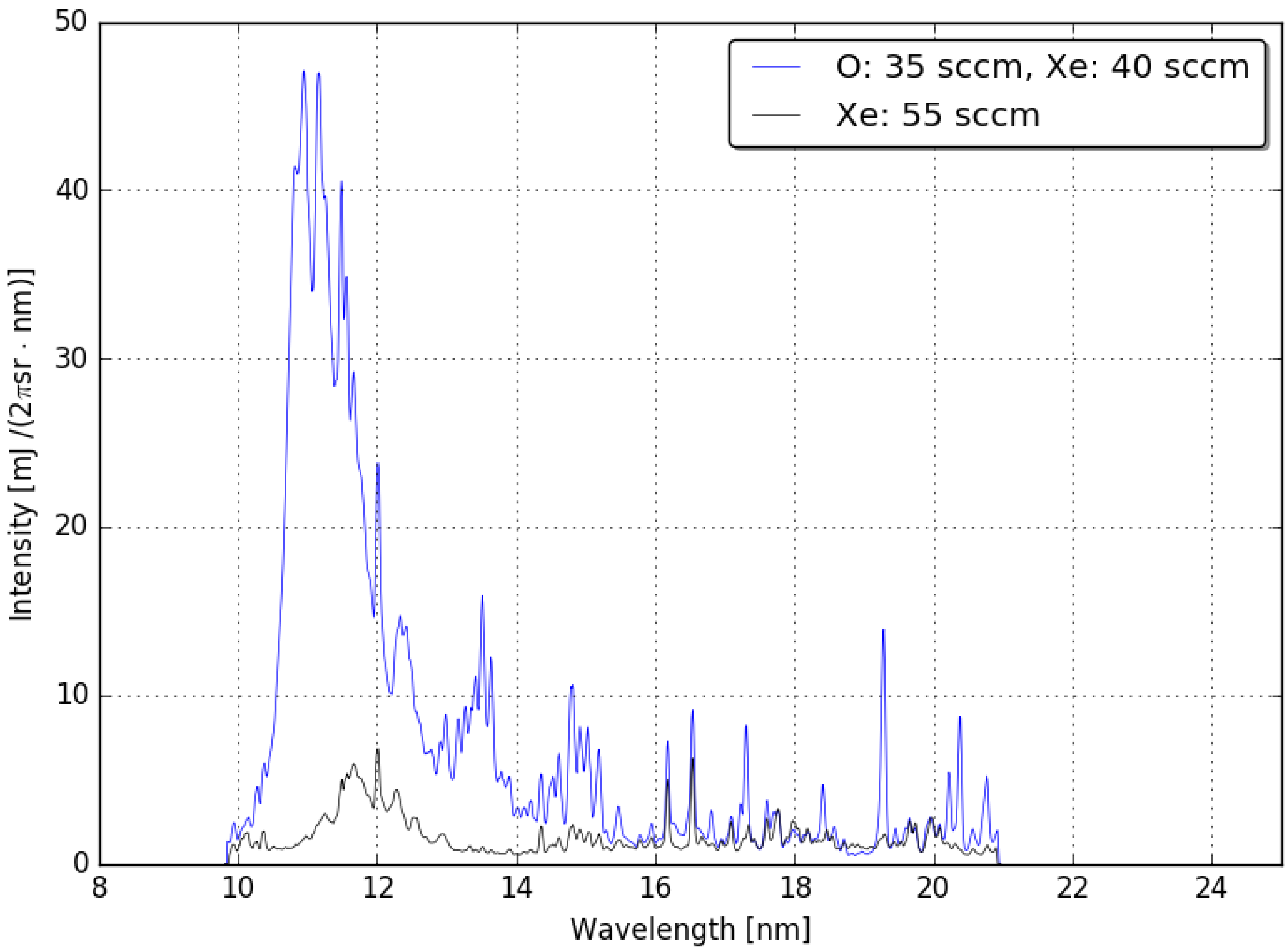
# Gas discharge plasma EUV source (GDP)


- Cylindrical EUV emitting volume 150 – 750 µm
- Up to 3 kHz repetition rate with 2.3 J (FS-5420 up to 10 J) discharge energy
- Pulse length 10 – 100 ns
- Peak radiance:
  - $100 \dfrac{\mathrm{W}}{\mathrm{mm^2\ sr}}$ (@ 10.9 nm Xe/Ar, 2 kHz, 4% bandwidth, UTA)
  - $8 \dfrac{\mathrm{W}}{\mathrm{mm^2\ sr}}$ (@ 13.5 nm Xe/Ar, 1.5 kHz, 3.2% bandwidth)
  - $0.4 \dfrac{\mathrm{W}}{\mathrm{mm^2 sr}}$ (@ 17.3 nm O, 2.5 kHz, <0.1% bandwidth)
- > 300 Mio. pulses before maintenance (depending on working gas)
- Small footprint (4 $m^2$), simple maintenance and adjustment

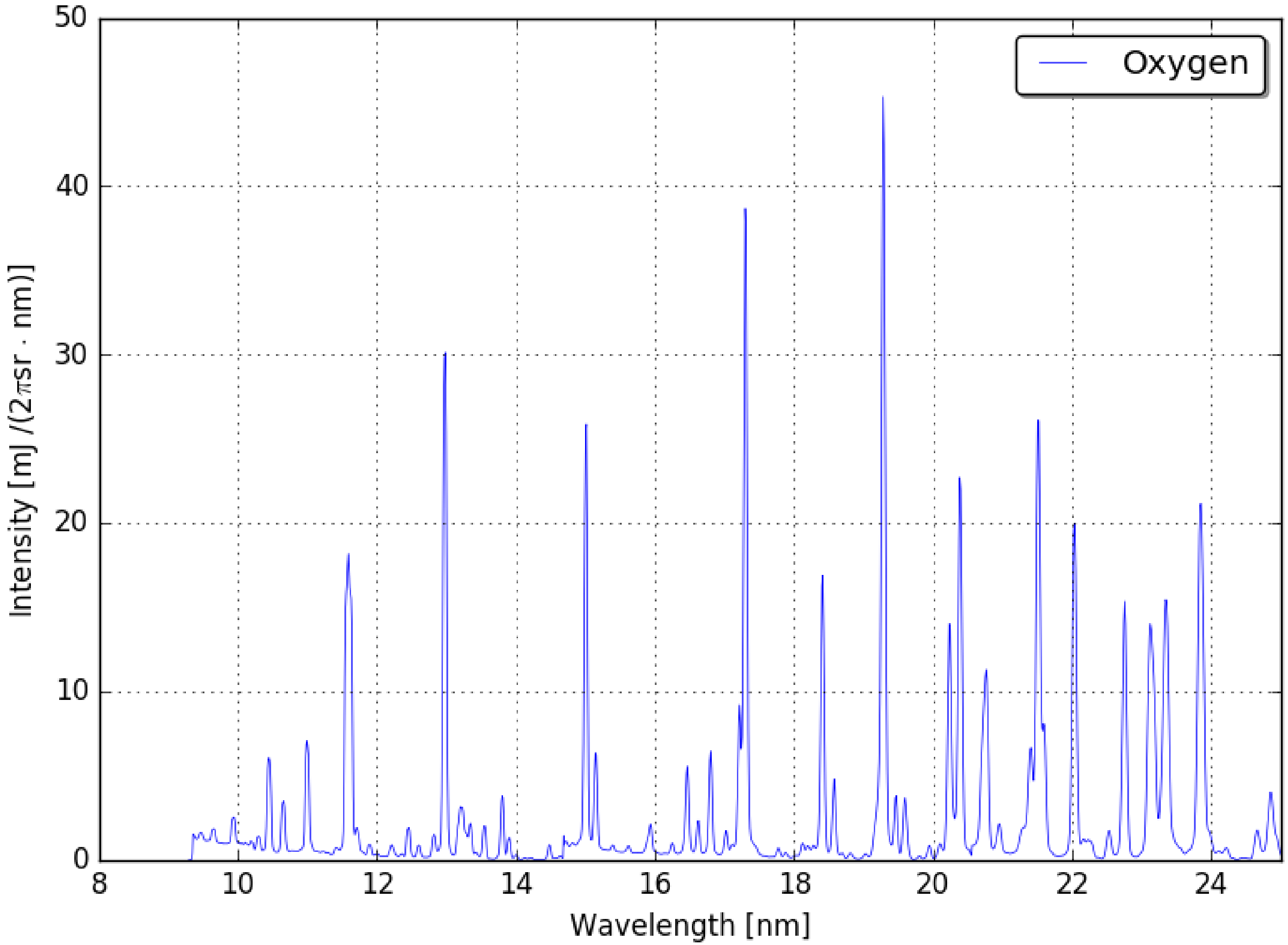
*K. Bergmann, S. Danylyuk, L. Juschkin, J. Appl. Phys.,* ***106*** *(7), 2009*



# Typical emission spectrum GDP - Xenon

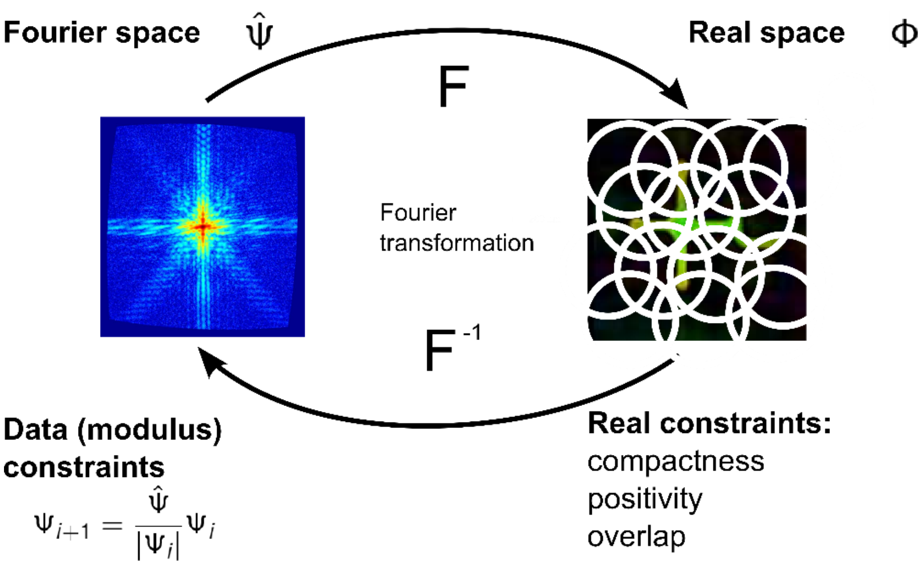


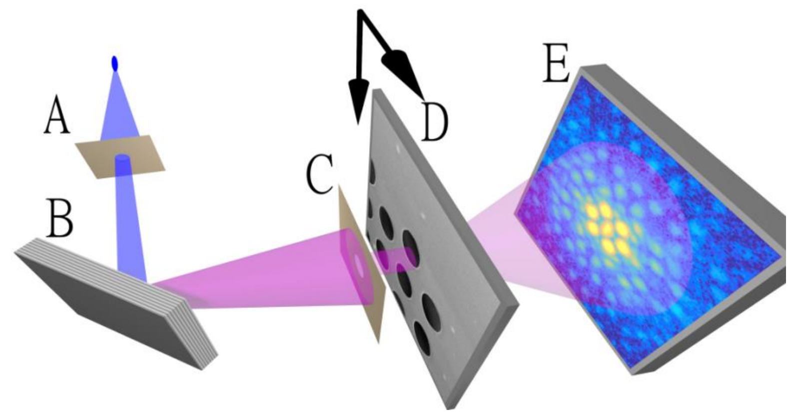
# Typical emission spectrum GDP - Oxygen



# Ptychography

- Scanning Coherent Diffractive Imaging
- Uses overlap information as real space constrain
  - Nyquist theorem requires an overlap of larger than 50% (in theory)
- Spatial incoherence does not influence field of view but scanning time
- Ptychography needs stable source during measurement
- Multi-wavelength reconstruction: $\Psi_{tot} = \sum a_i |\Psi_i|$



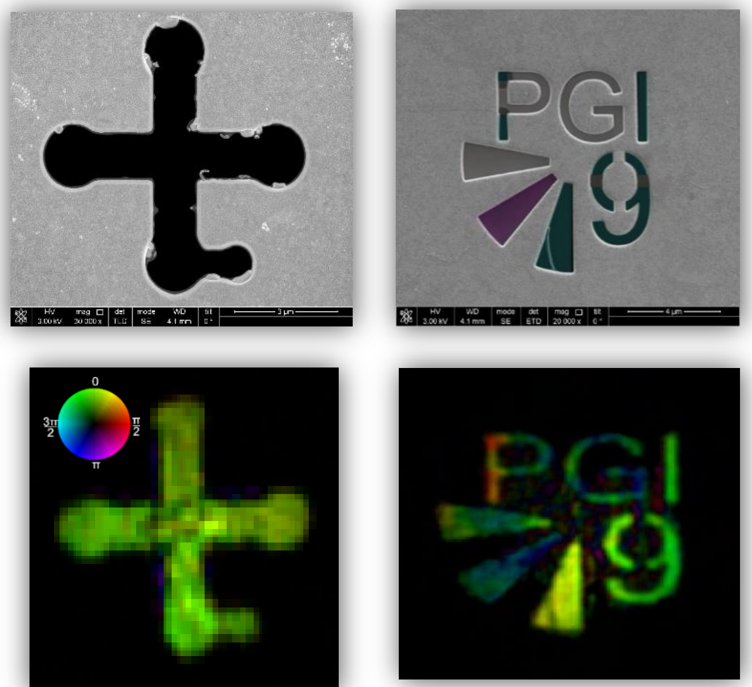




J. M. Rodenburg, H. M. Faulkner, “A phase retrieval algorithm for shifting illumination”, *Applied Physics Letters* **85** (20), 4795 (2004)

# Coherent imaging results with DPP source – presented last year

**@ 17.3 nm oxygen line**

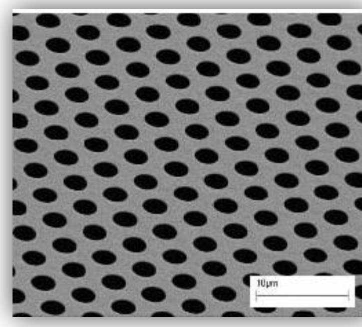
## CDI

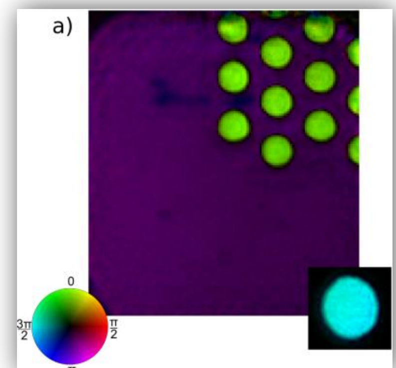


- Resolution ~ 200 / 110 nm
- 600 s – 1000 s exposure time

*J. Bußmann, et al., SPIE Proceedings , 95890L (2015)*

## Ptychography





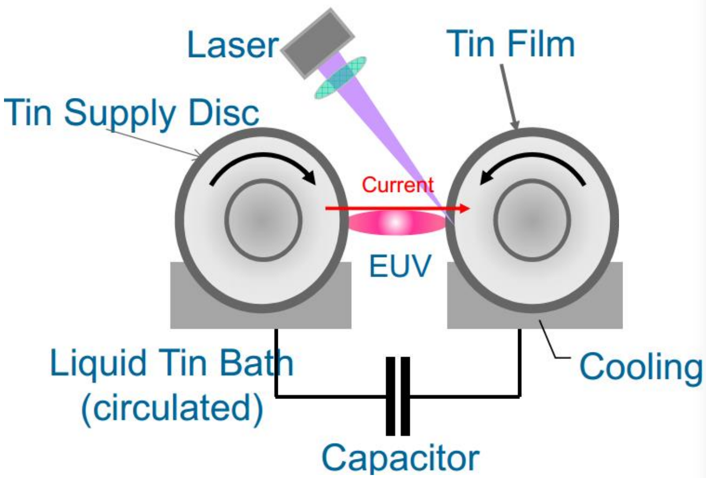

- Resolution ~ 250 nm
- Field of view ~ 25 µm x 25 µm
- Integration time ~ 30 s per position
- Recovery of refractive index
- Multi-wavelength reconstruction

*M. Odstrcil, et al., Opt. Lett.* ***40,*** *5574 (2015)*

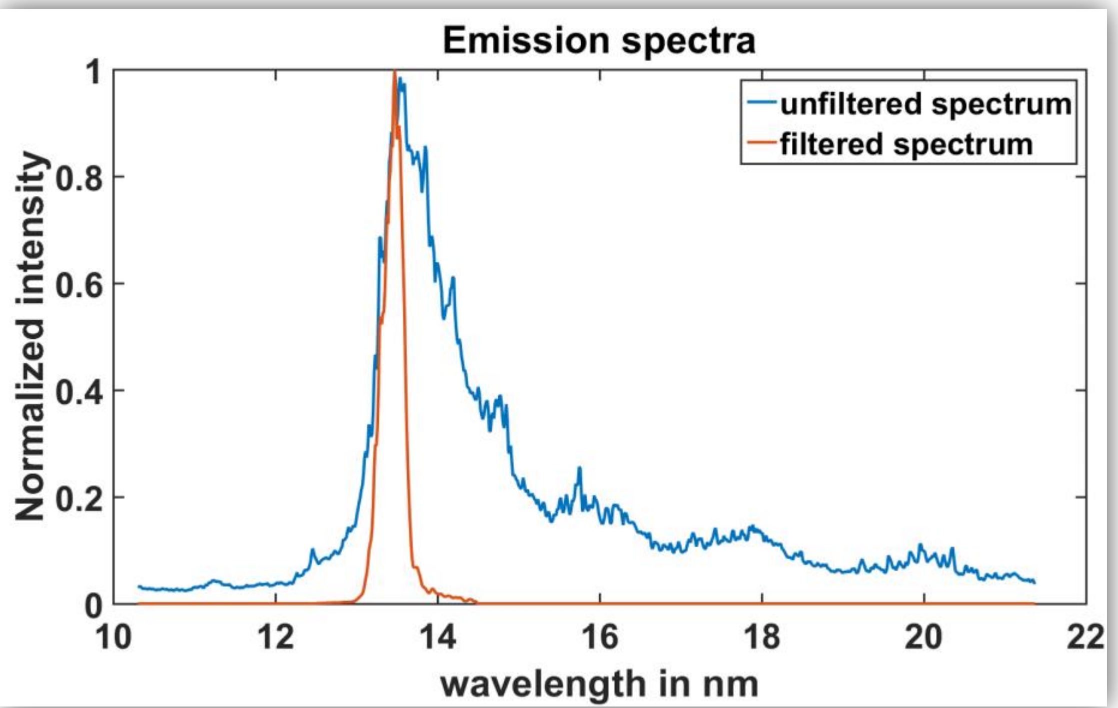
# Ptychography with laser assisted industrial DPP source (BLV/Ushio)

Presentation S15

- Liquid tin based EUV source by USHIO Inc.
- Up to $145\,\frac{\mathrm{W}}{\mathrm{mm^2 sr}}$ radiance @9 kHz repetition rate
- Up to $300\,\frac{\mathrm{W}}{2\pi sr}$ in-band EUV power (w/o debris mitigation)

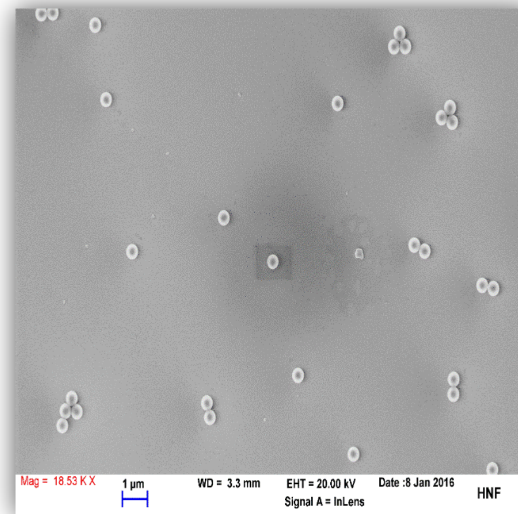


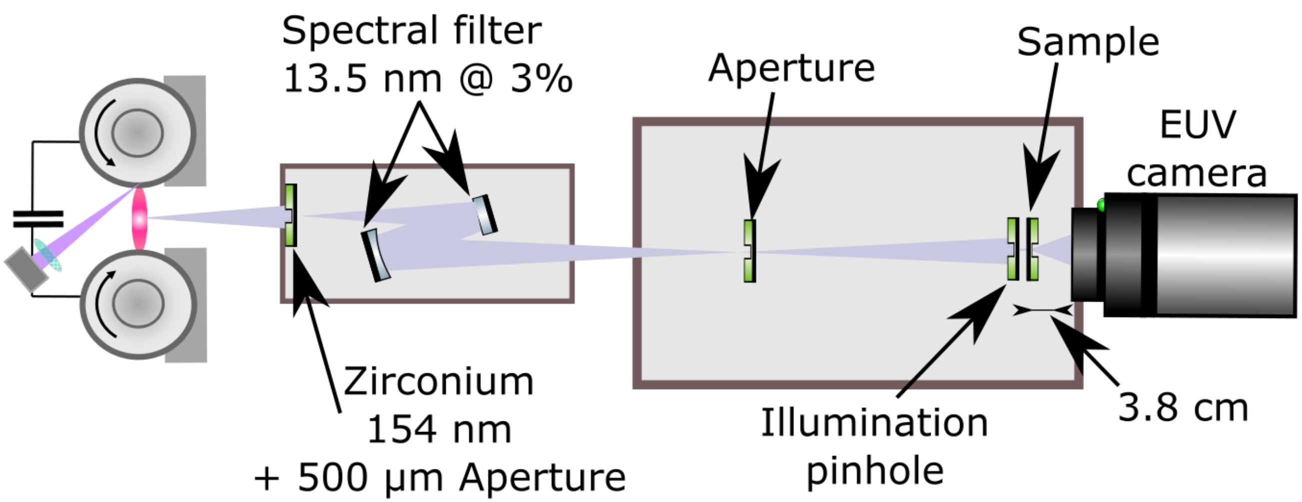

*Y. Teramoto, et al., SPIE Advanced Lithography (2016)*



# Ptychography with laser assisted industrial DPP source (BLV/Ushio)

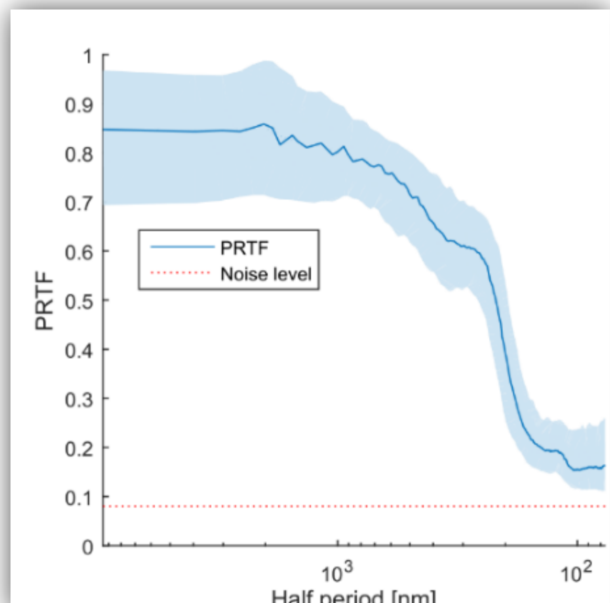
- Source radiance set to $36 \frac{\mathrm{W}}{\mathrm{mm}^2\,\mathrm{sr}}$
- Set of 2 ML mirrors for spectral filtering with ~ 5% transmission @ 13.5 nm and overall 2.2% BW
- Coherent photon flux density on sample ~ $3 \cdot 10^3 \frac{\mathrm{photons}}{\mu\mathrm{m}^2\mathrm{s}}$
- 400 nm spheres on a 50 nm silicon nitride membrane
- 200 scanning positions each 30 s exposure time
- ~ 56 µm total field of view

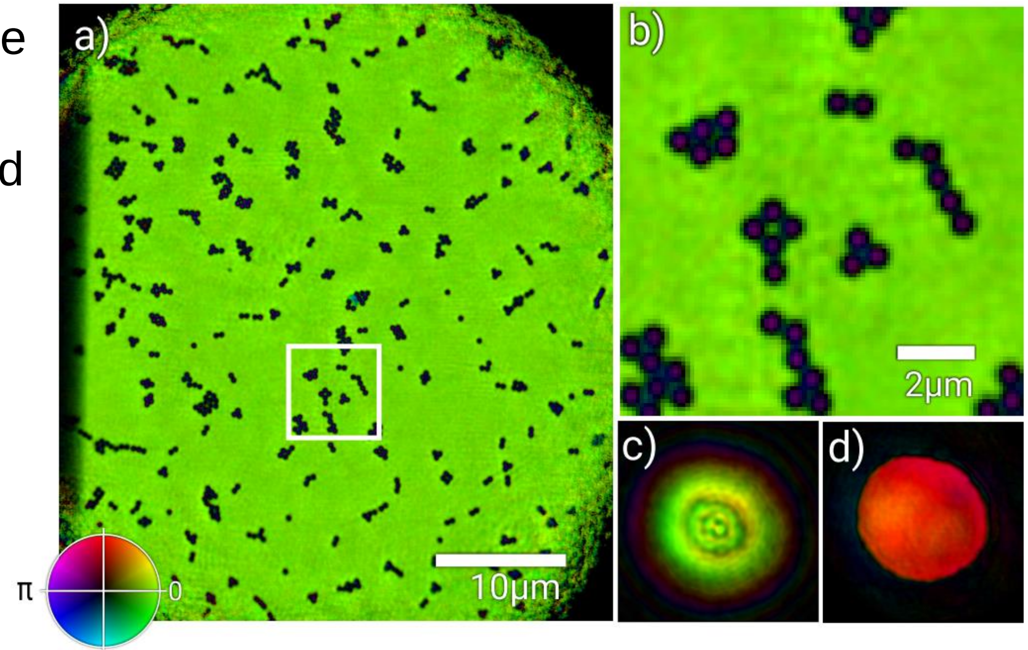


# Ptychography with laser assisted industrial DPP source (BLV/Ushio)

- Polyspheres are partly transmissive for 13.5 nm
- Phase and amplitude reconstructed
- 100 nm resolution
- Resolution is limited by radiant exposure (coherent photon flux density times exposure time)

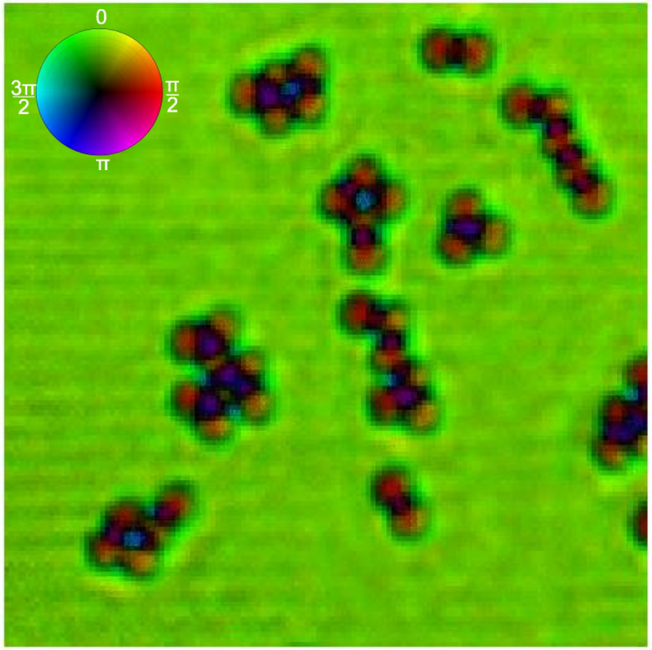



- Used reconstruction code: *M. Odstrcil, et al., Opt. Express **24,** 8360 (2015)*
- Further Details: *J. Bussmann, et al., 2015 JARA-FIT Annual Report (2016)*

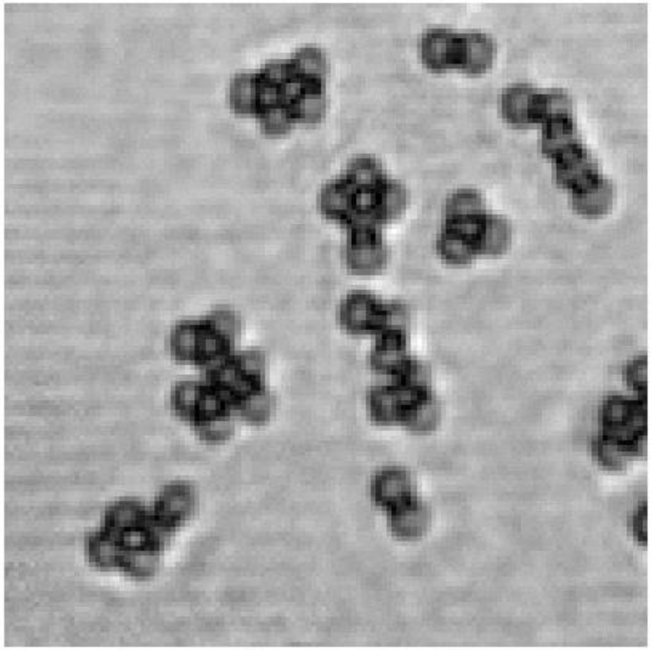
# Through focus propagation

- “Mimicking” through pellicle detection




**Phase**

Propagation distance -6 um



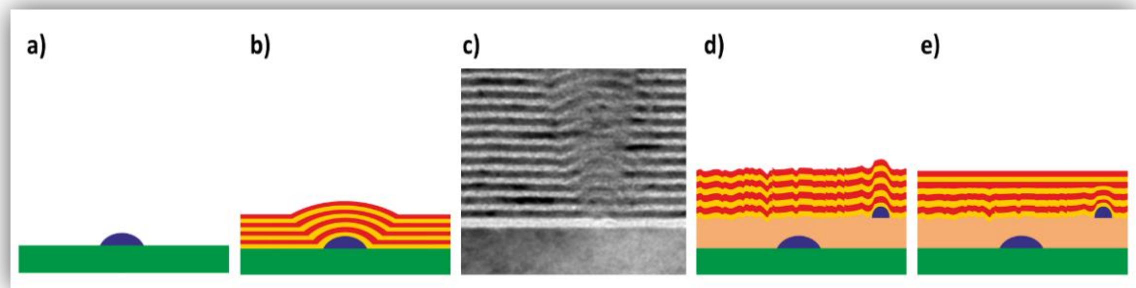
**Amplitude**

- 3d reconstruction possible

# Application of ptychography for detecting phase defects in multilayers

- Defects in ML mirrors may lead to a distortion of the image by introducing phase shifts and amplitude attenuation / defects on wafer
- Dark-field microscopy allows fast detection of defects, CDI / ptychography is able to reconstruct the phase and amplitude damage of the defect
- Fabrication and characterization of programmed defect arrays at the cleanroom HNF, Forschungszentrum Jülich
- Multilayer deposition at optiXfab. company
- Defect inspection at RWTH/FZJ

**Project aims on development of deposition techniques to fabricate defect-less multilayers**




Supported by:

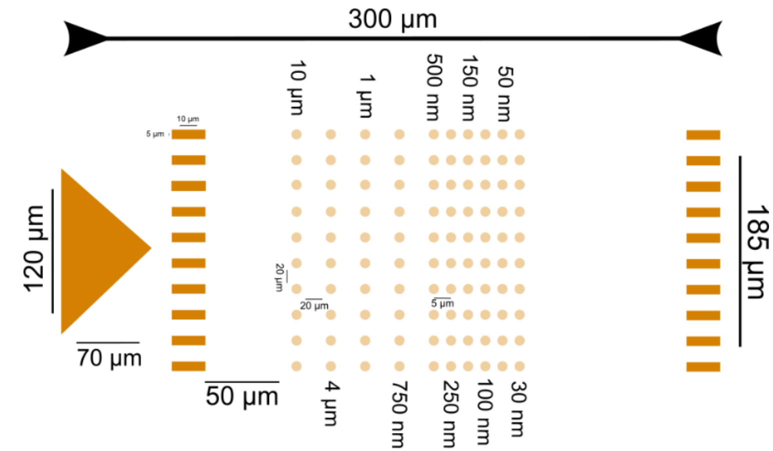
# Programmed defect arrays fabrication at Helmholtz Nanoelectronic Facility (HNF)

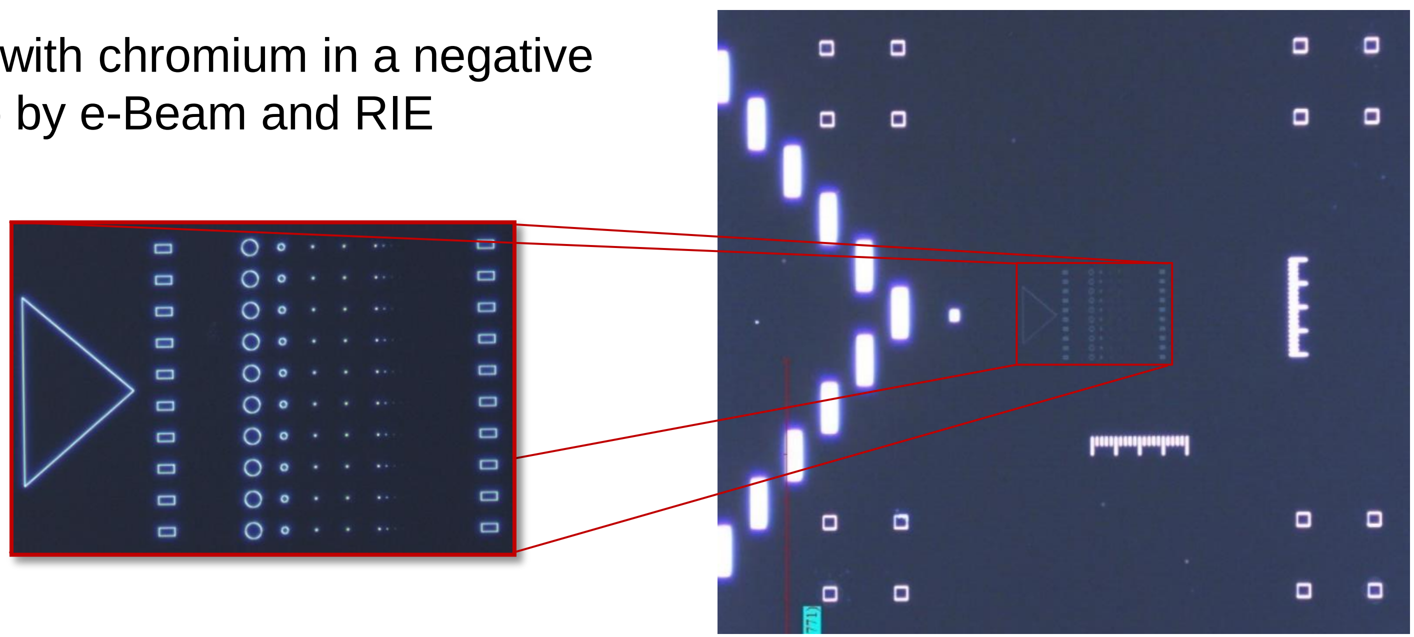
**HNF at Forschungszentrum Jülich**

- Opened in 2013, 1000 m$^2$ clean room (Class 1-3), VDI DIN 2083, GMP and SIA
- User access to infrastructure
- Separate instruments / areas for II / IV, III / V and bio-hybrid microfabrication

# Fabrication of defect array samples

- Defects are placed in / on standard silicon wafer
- Defect pit / bump height / depth of 20 nm
- Defect diameter from 10 µm – 30 nm
- Pits defined in a positive lithography step by e-Beam lithography and reactive ion etching
- Bumps created with chromium in a negative lithography step by e-Beam and RIE

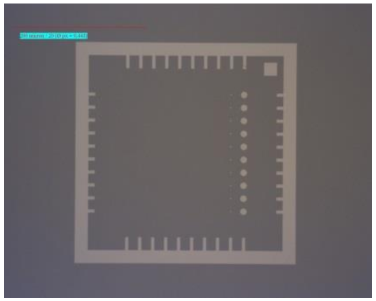


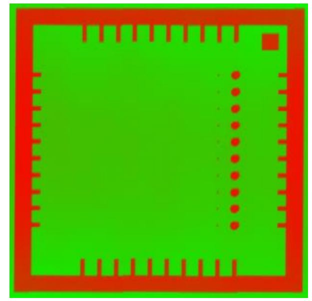
# Standard inspection techniques

Helmholtz Nanoelectronic Facility

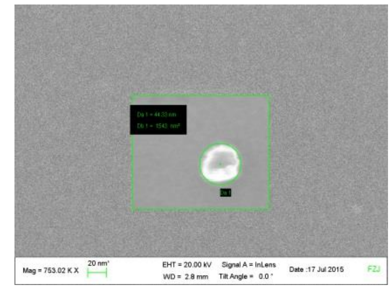
www.hnf.fz-juelich.de



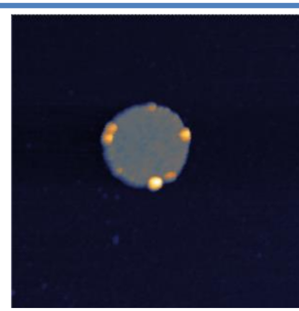

Visible light microscopes



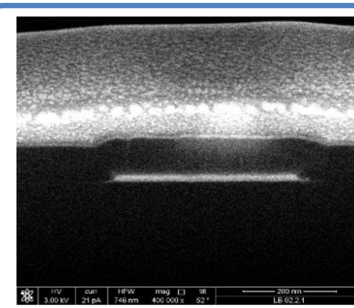

White light interferometer




Scanning electron microscope




Atomic force microscope




Focused ion beam



Experimental Physics of Extreme Ultraviolet

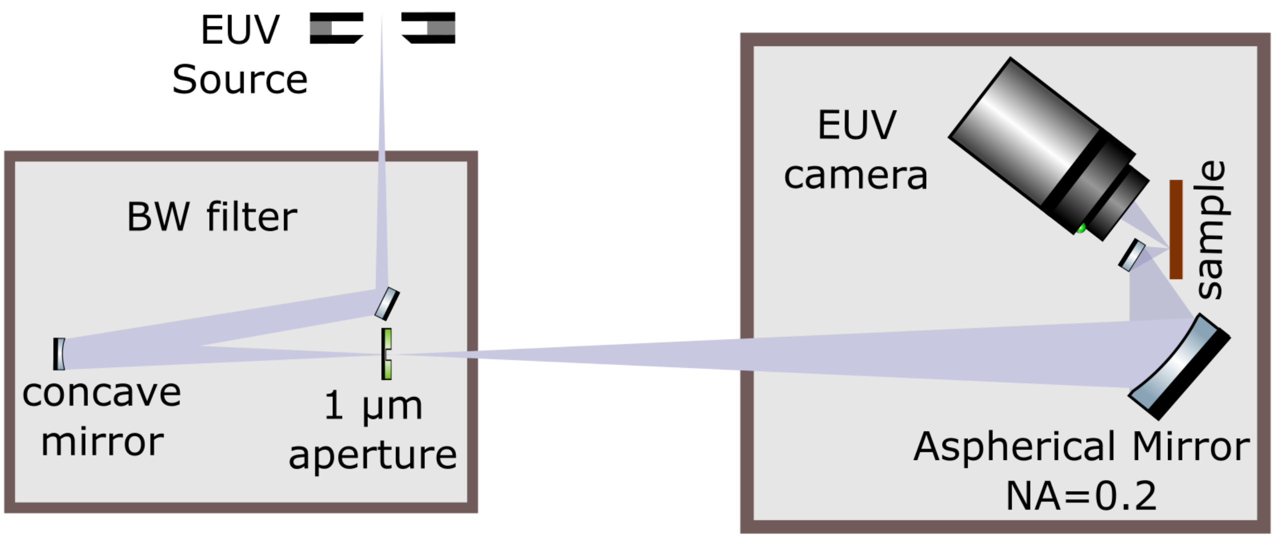
# Traditional actinic inspection methods

- Blank mirror inspection
  - Dark field inspection (*L. Juschkin, et al. J. Phys. Conf. Ser.* ***186,*** *012030 (2009)),* Scatterometry, Reflectometry *(S. Danylyuk, et al. Phys. Status Solidi* ***12,*** *318–322 (2015)*)
  - …
- Blank and mask inspection (for lithography)
  - Characterization by resist-printed images, SHARP (M. *Benk, EUVL 2015, Maastricht),* Arial Image Measurement System *(Carl Zeiss AIMS$^{TM}$ ),* ReScan II *(P. Helfenstein, et al., SPIE* ***97761F*** *(2016)*)
  - …
- Allow large field of view and high resolution but …
- Require synchrotron beamline or expensive large diameter, high quality optics

⇒ Development of a „cheap“ and „simple“ tool / schematic for EUV blank and mask inspection

# Actinic inspection of multilayer defects with reflection ptychography

- Establishment of (near-field) reflection ptychography with an aspherical, high NA mirror at 13.5 nm
- Strongly curved illumination through 1 µm spatial filtering pinhole to achieve coherent illumination of 8 cm aspherical mirror in reasonable distance
- Variable bandwidth ($\frac{\Delta\lambda}{\lambda} < 2\%$) through double multilayer setup
- Due to setup delay, intermediate experiment on near-field ptychography was conducted

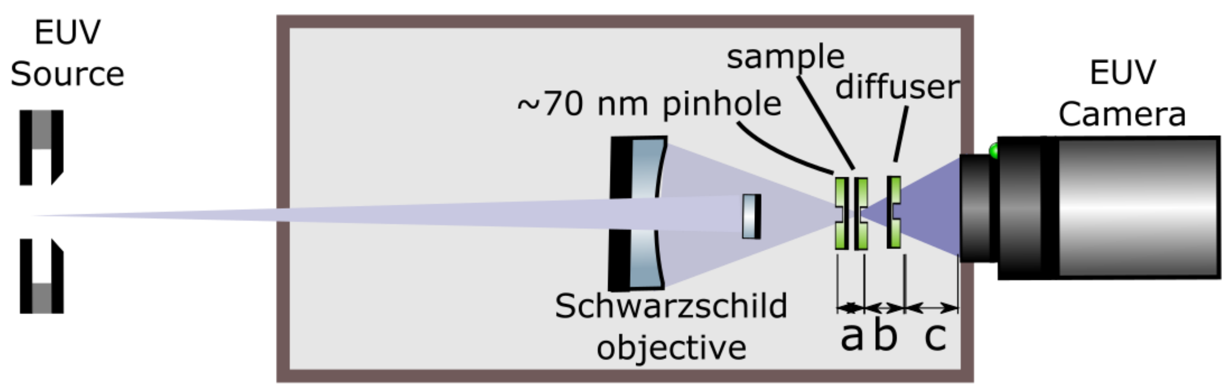


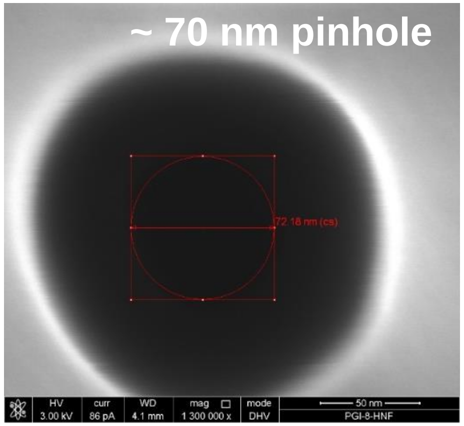
JÜLICH
FORSCHUNGSZENTRUM

# Nearfield ptychography with structured illumination

- Phase / amplitude response from the defects will be weak and sparse
- Stockmar et al.* proposed a method to achieve reliable ptychographic reconstruction even for weak scatterer
- Relaxed requirements on coherence and increased usage of detector size
- 40x de-magnified source image by Schwarzschild objective to achieve focus size of ~ 10 µm, strong Fresnel scaling due to high NA mirror and short distance to detector
- Pinhole acts as new light source and determines spatial coherence / final resolution
- Goal: 50 µm field of view with 50 – 100 nm resolution

* M. Stockmar, et al., Scientific Reports, 3 (2013)



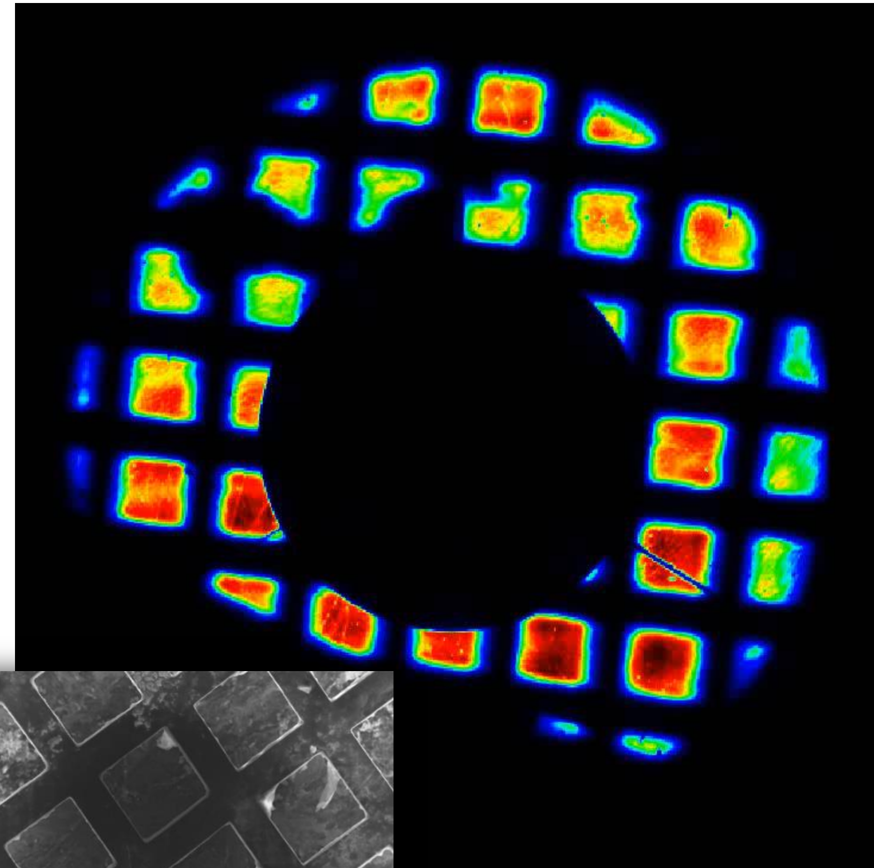


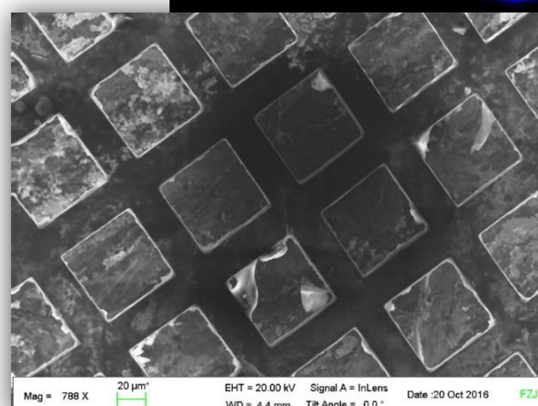

EUV Experimental Physics of Extreme Ultraviolet

RWTH AACHEN UNIVERSITY

# Near-field ptychography (with structured illumination)

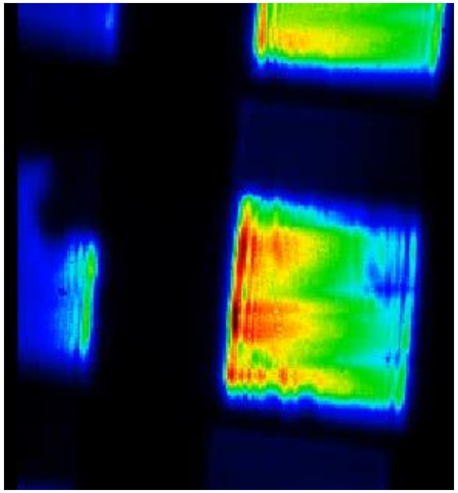
- Standard TEM-grid was used as a dummy sample
- Run without diffusor
- Aspect ratio between EUV absorber and 70 nm pinhole limits light transmission below recognition level
- Test with larger „natural“ pinhole in absorber (~ 5 µm)
- 190 images with 0.5 s exposure time and 1 s read out
- ~ 10x magnification of sample
- No scattering visible by eye

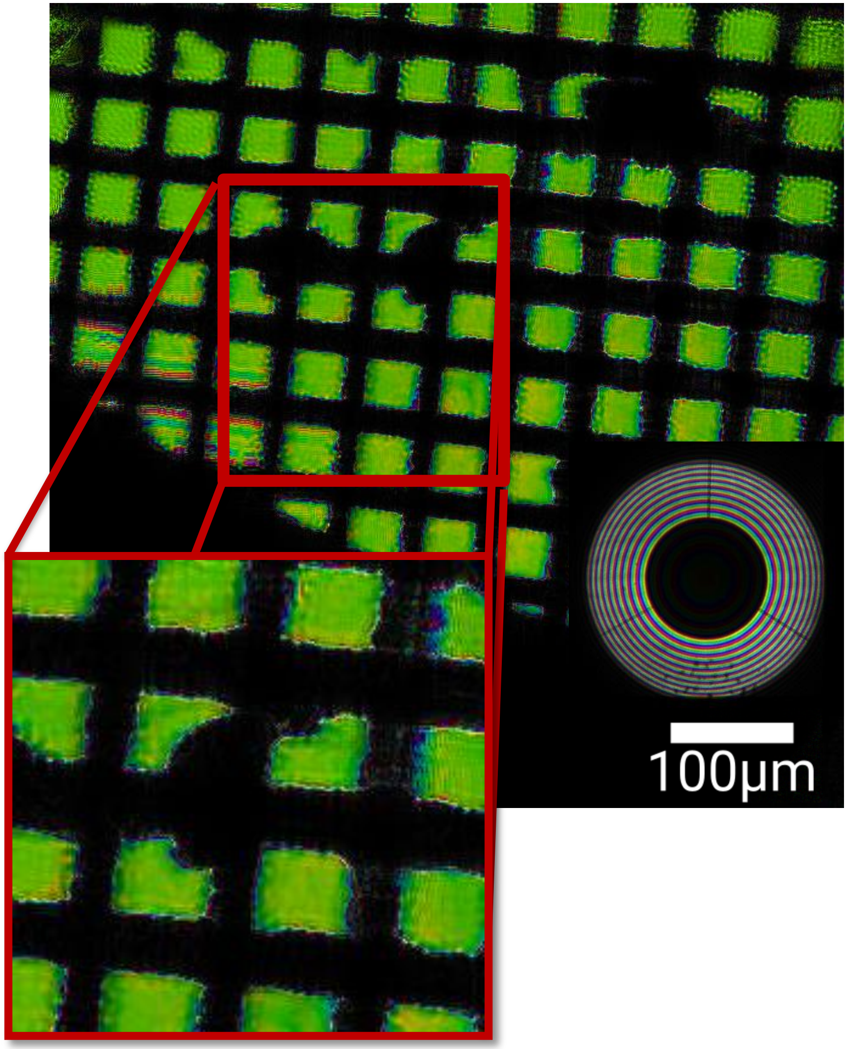




# Nearfield ptychography

- Estimated resolution ~ 2 µm
- Limited coherence due to pinhole size
- Reconstruction of illumination wavefront is feasible also with low-scattering sample and speckle-less pattern
- Reconstructed illumination wavefront can be used for adjustment of Schwarzschild objective
- *Measurements with smaller pinholes are work in progress*

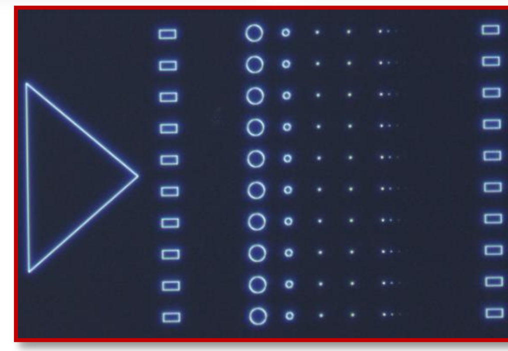




# Summary and outlook

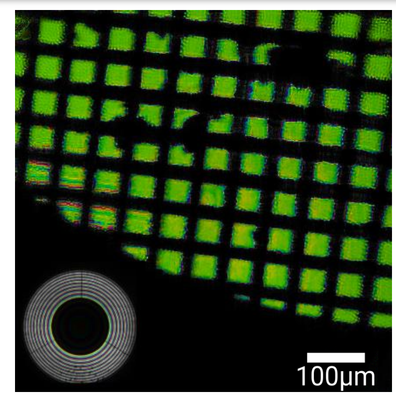
- Successful utilization of discharge plasma sources for coherent imaging experiments
- Experimental demonstration of far- and near-field CDI and ptychography
- Application of ptychography with industrial tin-based LDP source
- Successful acquisition of phase information of nanoparticles on a membrane and of illumination wavefront





***Future plans:***

- Application of ptychography for detecting phase defects in multilayers
- Validation of the metrology technique with programmed defect arrays



# Thank you very much for your attention!